

# Feedhorn-Coupled Transition-Edge Superconducting Bolometer Arrays for Cosmic Microwave Background Polarimetry

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**Abstract**—NIST produces large-format, dual-polarization-sensitive detector arrays for a broad range of frequencies (30-1400 GHz). Such arrays enable a host of astrophysical measurements. Detectors optimized for cosmic microwave background observations are monolithic, polarization-sensitive arrays based on feedhorn and planar Nb antenna-coupled transition-edge superconducting (TES) bolometers. Recent designs achieve multiband, polarimetric sensing within each spatial pixel. In this proceeding, we describe our multichroic, feedhorn-coupled design; demonstrate performance at 70-380 GHz; and comment on current developments for implementation of these detector arrays in the advanced Atacama Cosmology Telescope receiver.

## I. INTRODUCTION

Cosmic microwave background (CMB) observations have been instrumental in forming the standard model of cosmology. Yet this model is thought to be incomplete as it raises several profound questions about the formation, constituents, and current expansion of the cosmos. Polarization measurements of the CMB are a known way to probe these questions [1] as they constrain cosmic inflation, the growth rate of structure, and neutrino physics. Experimental progress in this field is rapid. First detections of CMB B-mode polarization at both large and small angular scales having been reported [2]–[4] as have high-precision measurements of E-mode polarization [5]–[7]. However, furthering our understanding of cosmology through CMB polarization measurements requires next-generation polarimeters of increased focal plane sensitivity and spectral coverage.

Large arrays of polarization-sensitive detectors are an enabling technology for current and next-generation CMB experiments, and several architectures exist [8]–[10]. This proceed-

ing concerns a NIST-developed technology based on monolithic arrays of multiplexed transition edge superconducting (TES) bolometers that are feedhorn-coupled [11]. Feedhorns have heritage in CMB satellite missions from COBE to Planck. Our silicon platelet feedhorn technology [12] enables a scalable, feedhorn-coupled approach, which achieves high-sensitivity while simultaneously maintaining the systematic error advantages of defining polarized beams with corrugated feeds. Detectors of this architecture have been instrumented in several ground-based experiments [13]–[16] and have been proposed for use in the Japanese CMB satellite mission Lite-BIRD [17]. This concept is also the baseline for the focal plane of the recently proposed European satellite mission CoRE+ [18].

Our initial designs were single-frequency, and have been described in a series of papers [11], [19]–[21]. We have since expanded the design to realize single-mode detection in two frequency bands within one spatial pixel [22], [23], which increases both the sensitivity and spectral resolution of cameras that make use of these multichroic detectors. Arrays of 90/150 GHz dichroic detectors have now been implemented in ACTPol [15], which marks the first ever multichroic detector array to be deployed on a CMB experiment.

In Sec. II, we review the multichroic design, which is scalable in frequency up to 682 GHz, the superconducting gap of niobium. We note that the development of dual-polarization sensitive detectors that operate up to 1400 GHz, based on microwave kinetic inductance detectors (MKIDs), are discussed in separate work in these proceedings [24]. In Sec. III we present measurements from 80-380 GHz that characterize the performance of the multichroic detectors. In Sec. IV we comment on current development items for implementation in Advanced ACT, the third-generation receiver for the Atacama



Fig. 1. Multichroic, feedhorn-coupled detector architecture. Left: A silicon platelet, corrugated feedhorn array defines the angular response of detectors. The feeds have 2.4:1 bandwidth. Middle: TES-based, polarization-sensitive detector array deployed on ACTPol for dual-band operation at 90 and 150 GHz. Right: Dichroic pixels include an ortho-mode transducer, microstrip filters, microwave hybrids and TES bolometers.

Cosmology Telescope.

## II. DESIGN

Fig. 1 illustrates the feedhorn-coupled, multichroic array architecture. A 150 mm diameter feedhorn array couples light from telescope foreoptics. Orthogonal components of linear polarization launch onto separate, superconducting mm-wave transmission lines by use of a planar ortho-mode transducer made of Nb. We partition the broadband frequency content from the waveguide into two frequency bands with a diplexer and 5-pole, quarter-wavelength microstrip filter made of Nb and SiO<sub>2</sub> insulator. Changing the length and the width of each microstrip stub tunes the observation passband center frequency and width respectively. Implemented designs have center frequencies at 90 and 150 GHz or 230 and 340 GHz, each with  $\sim 30\%$  fractional bandwidth. We achieve mode-cleaning by use of a microwave hybrid [25], which routes power from the lowest order waveguide mode to a Au resistor placed on a transition edge superconducting (TES) bolometer. Higher order modes dissipate on the substrate. We use separately optimized hybrids for each band. In this manner, the designed pixel achieves polarimetric sensing over a 2.3:1 bandwidth ratio.

This design allows the TES bolometer to be separately optimized from the optical coupling approach, to meet the requirements of a specific experiment. We control the saturation power ( $P_{\text{sat}}$ ) of the bolometer by the geometry of the thermally isolating silicon nitride legs, and values suitable for ground-based or satellite-based observations have been demonstrated with noise consistent with fundamental limits [26]. Mo/Cu bilayer TES bolometers with transition temperatures ( $T_c$ ) over the range 100-500 mK have been implemented in CMB experiments. This  $T_c$  range enables the use of several cooling technologies (ADR, dilution refrigeration, <sup>3</sup>He sorption). The impedance of these devices is well suited to time domain SQUID multiplexing [27] or microwave SQUID multiplexing [28]. We have also deployed  $\sim 1 \Omega$  TES bolometers made of an Al:Mn alloy [29] in SPTpol. This impedance couples well to frequency division multiplexing [30]. Future TES arrays will be based on Al:Mn alloys and are discussed below.

The arrays are fabricated in the NIST, Boulder Microfabrication Facility using standard micro-lithographic techniques.

Antennas, transmission lines, passband filters, microwave hybrids and TES bolometers are integrated onto a single detector wafer, which improves manufacturing scalability. All arrays to date have been fabricated on 75 mm diameter silicon wafers. Future arrays will be fabricated on 150 mm silicon wafers.

## III. RESULTS

We demonstrate the basic functionality of multi-band, feedhorn-coupled detectors in single pixels with detection at 90 and 150 GHz, and at 230 and 340 GHz. Fig. 2 demonstrates on-chip frequency selection. The 90 GHz and 150 GHz bands are measured by use of the spatial pixel displayed in Fig. 1, and the 230 GHz and 340 GHz are measured by a frequency-scaled version of the 90/150 GHz dichroic detector. We perform the measurements with a Martin-Puplett type Fourier transform spectrometer that couples to the horn/detector package by use of beam filling reflective optics. The cryostat optical access contains PTFE and nylon thermal filters to block infrared light. These three filters have single-layer anti-reflection coatings optimized at  $\sim 120$  GHz, and the data show evidence of fringing above 200 GHz.

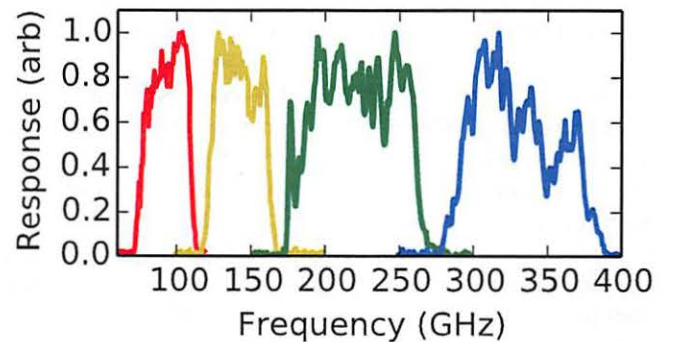


Fig. 2. Measured observation passbands defined with on-chip filters. The 90 GHz and 150 GHz bands are detected in a single spatial pixel. The 230 GHz and 340 GHz passbands are detected in a separate, frequency-scaled spatial pixel.

Fig. 3 shows the 2D angular response pattern of the integrated silicon feedhorn and 90/150 GHz detector pixel in both polarizations and in both bands. We acquire the data by



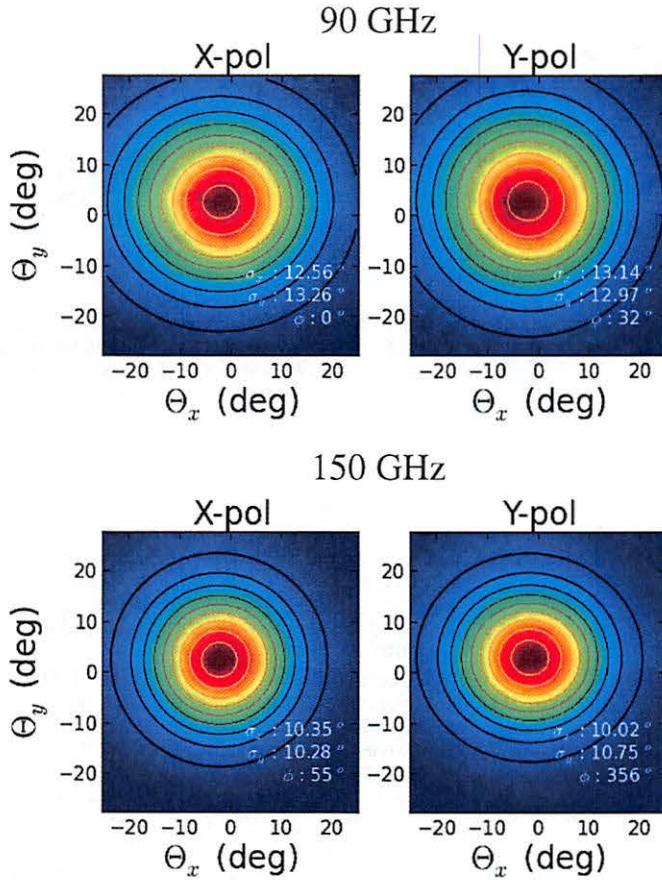


Fig. 3. Angular response of Si platelet, horn-coupled 90 and 150 GHz dichroic detector measured in a cryogenic system. Both X and Y polarization beams plotted on a linear color scale are shown in both bands. Contours are fits to a 2D Gaussian profile, and the stated  $\sigma_{x,y}$  within each plot are the Gaussian beam waists in orthogonal directions.

raster scanning a chopped thermal source on a flat plane in front of the cryostat window. We correct for flat mapping. The displayed contours are fits to 2D Gaussian profiles. Using the entire data-set, peak residuals to the Gaussian fits are  $\sim 4\%$ . We list the fitted Gaussian beam waists  $\sigma_{x,y}$  in orthogonal directions within each plot. This measurement demonstrates that the beams are circularly symmetric and well-matched in polarization, which is of considerable importance for a pair-differencing detection scheme. [31], [32].

The changing beam waist with frequency due to diffraction illustrates the limitation of a multichroic approach. Frequency bands that share a common aperture cannot optimally match telescope foreoptics. We note that 2:1 bandwidth divided into two sub-bands provides nearly optimal mapping speed for an array in both bands, and that mapping speed for additional bands falls off quickly with increasing bandwidth [23]. For this reason, we developed 2:1 bandwidth ratio dichroic pixels. A 255-element (1020 TES) array of 90/150 GHz pixels has been fabricated and deployed on ACTPol, with first observations of this multichroic array taking place in early 2015.

#### IV. ON-GOING AND FUTURE WORK

Near-term efforts focus on scaling the technology in frequency and in wafer size for implementation in Advanced ACT (AdvACT), a third generation receiver for the Atacama Cosmology Telescope. The planned instrument consists of dichroic arrays at 30/40 GHz, 90/150 GHz and 150/220 GHz with a total of 5,792 TES bolometers. Using the measured on-sky detector sensitivity from the first season of ACTPol observations [5], we project that the AdvACT instantaneous sensitivity to temperature will be  $5.4 \mu\text{K}_{\text{cmb}} \sqrt{\text{Hz}}$  at 150 GHz.

Significant increased sensitivity per unit focal plane array and simplified array assembly motivate scaling the detector wafer size to 150 mm. Spatial uniformity across the entire wafer size for all material depositions is key. Of particular importance to TES fabrication is uniformity in transition temperature  $T_c$ . By use of a 2000 ppm Al:Mn alloy, we find  $T_c = 142 \text{ mK}$ , which is near the target value for AdvACT and is uniform across the 150 mm wafer to 1% (see Fig. 4 left panel). Furthermore, we fabricated TES bolometers using these Al:Mn films as the sensor material and find noise consistent with thermal fluctuation noise (Fig. 4 center and right panel).

In the full, optically coupled pixels, we expect an improvement in coupling efficiency by switching the microstrip dielectric material from  $\text{SiO}_2$  to  $\text{SiN}$ . Previous fabrications with  $\text{SiO}_2$  showed non-negligible dielectric loss and deposition variability of the relative permittivity, which shifts the passband away from the designed band. Initial measurements of  $\text{SiN}$  deposited dielectrics, based on the technique described in [33], suggest that the absolute dielectric loss is 1%/mm of transmission line at 150 GHz, with lower variability in the relative permittivity as compared to  $\text{SiO}_2$ . We are currently fabricating an array of 150/220 GHz detectors to explore the performance of these design, fabrication and material changes.

#### ACKNOWLEDGEMENTS

The development of multichroic detectors was supported by NASA grant NNX13AE56G.

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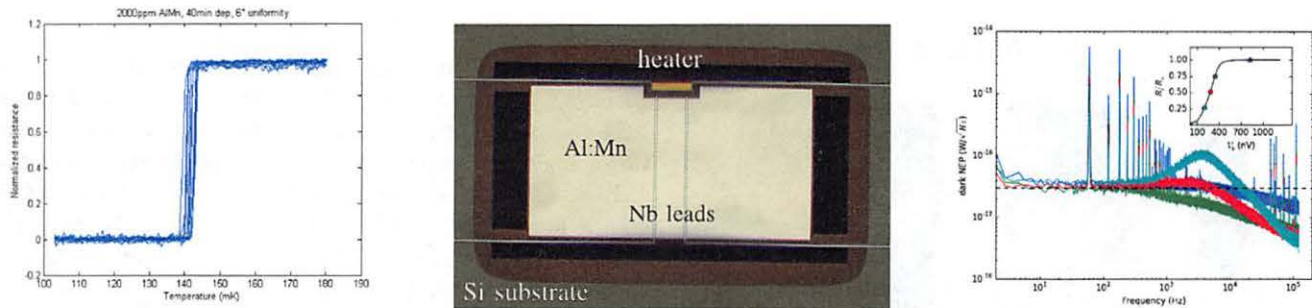


Fig. 4. Recent Al:Mn TES bolometer developments. Left: The superconducting Al:Mn transition for 16 samples across a 150 mm diameter wafer show 1%  $T_c$  non-uniformity. Middle: TES bolometer with Al:Mn sensor. The TES sensor area is defined by the two vertical Nb leads. Right: Noise measurements of the device shown in the middle panel referred to noise equivalent power by use of the low frequency responsivity. The low frequency NEP is consistent with expectations (dashed-black line) when biased at various points in the superconducting transition. These bias positions are displayed in the inset plot, which shows the normalized resistance as a function of voltage bias.

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